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Climatic Controls on Watershed Reference Evapotranspiration Varied during 1961–2012 in Southern China

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Research Impact Statement: Climatic controls on evaporative demand vary over time in a humid watershed. Accurately predicting future hydrological change due to climate change must consider changes in vapor pressure deficit.

ABSTRACT: Reference evapotranspiration (ET_o) is an important hydrometeorological term widely used in understanding and projecting the hydrological effects of future climate and land use change. We conducted a case study in the Qinhuai River Basin that is dominated by a humid subtropical climate and mixed land uses in southern China. Long-term (1961–2012) meteorological data were used to estimate ET_o by the FAO-56 Penman–Monteith model. The individual contribution from each meteorological variable to the trend of ET_o was quantified. We found basin-wide annual ET_o decreased significantly ($p < 0.05$) by 3.82 mm/yr during 1961–1987, due to decreased wind speed, solar radiation, vapor pressure deficit (VPD), and increased relative humidity (RH). However, due to the increased VPD and decreased RH, the ET_o increased significantly ($p < 0.05$) in spring, autumn, and annually at a rate of 2.55, 0.56, and 3.16 mm/yr during 1988–2012, respectively. The aerodynamic term was a dominant factor controlling ET_o variation in both two periods. We concluded the key climatic controls on ET_o have shifted as a result of global climate change during 1961–2012. The atmospheric demand, instead of air temperature alone, was a major control on ET_o. Models for accurately predicting ET_o and hydrological change under a changing climate must include VPD in the study region. The shifts of climatic control on the hydrological cycles should be considered in future water resource management in humid regions.

(KEYWORDS: reference evapotranspiration; atmospheric demand; climate change; Qinhuai River Basin; FAO-56 Penman–Monteith model.)

INTRODUCTION

Climate change and human activities have altered global hydrological cycles (Christensen and Lettenmaier 2007; Brooks 2009; Cuo et al. 2009; Xu et al. 2016; Li et al. 2017; Yang et al. 2017; Hao et al. 2018a) including the evapotranspiration (ET) processes (Zalewski 2000; Xu et al. 2015), resulting in a series of environmental and socioeconomic impacts such as deterioration of water quality, increased runoff, and risk of floods (Roderick and Farquhar 2002; Grant et al. 2012; Hallegatte et al. 2013; Gao 2016; Gao and Sang 2017). ET is a key component of ecosystem water and energy balances (Hao et al. 2015a; Liu et al. 2017), and ET is also tightly coupled with the carbon cycle (Sun et al. 2011). Thus, understanding ET is important for quantifying watershed ecohydrological, meteorological, and ecological processes (Yang et al. 2012; Zhao et al. 2014).

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A widely used method to estimate actual ET is through quantifying reference ET (ET_o) (Lu et al. 2005; Liu et al. 2010, 2017), a term that closely resembles the ET from a uniform and well-watered underlying surface with actively growing green grass. McMahon et al. (2013) provided a summary of techniques (Penman, Priestley–Taylor, Thornthwaite, Makkink, and FAO-56 Penman–Monteith [P–M]) to estimate ET_o and suggested that the FAO-56 P–M model was preferred in humid regions. This model has also been recommended as the sole standard method for calculating ET_o by the Food and Agriculture Organization of United Nations (Allen et al. 1998). It explicitly incorporates both radiometric and aerodynamic terms and has been widely used and aroused the interest of researchers (Liu et al. 2010; Yin et al. 2010; Tabari et al. 2011; Irmak et al. 2012; Jhajharia et al. 2012; Darshana et al. 2013; Zhang et al. 2013; Yang et al. 2014; Shan et al. 2015; Xu et al. 2015; Zhao et al. 2015; Fan et al. 2016; Gao et al. 2017).

Worldwide, numerous studies (Cohen et al. 2002; Xu et al. 2006, 2015; Liu et al. 2010; Yin et al. 2010; Tabari et al. 2011; Irmak et al. 2012; Jhajharia et al. 2012; Darshana et al. 2013; Zhang et al. 2013) have examined ET_o dynamics in different regions and reported increased, decreased, and even stable trends. The decreased ET_o was found in the Platte River Basin in central Nebraska of the United States (U.S.) during 1983–2007 (Irmak et al. 2012) and the Tons River Basin of central India during 1969–2008 (Darshana et al. 2013). These studies showed that decreased ET_o was observed in some regions despite the global temperature rise by 0.13°C per decade in the last five decades (Solomon 2007). The mechanisms and processes behind the climatic controls on ET_o under different climatic regimes have been examined (Cohen et al. 2002; Liu et al. 2010; Yin et al. 2010; Tabari et al. 2011; Irmak et al. 2012; Jhajharia et al. 2012; Zhang et al. 2013; Yang et al. 2014; Xu et al. 2015; Zhao et al. 2015). For example, Jhajharia et al. (2012) found that the decreased wind speed (WS) and net radiation overwhelmed the effect of increased air temperature and then caused the decreased ET_o in a humid region in northeastern India during 1978–2002. In western Iran, the increasing trend of ET_o was mainly caused by an increase in air temperature during 1966–2005 (Tabari et al. 2011). No changes in ET_o were found from 1964 to 1998 in Bet Dagan on Israel's central coastal plain where the effects of increased vapor pressure deficit (VPD) and WS were counterbalanced by the decreased solar radiation (R_s) (Cohen et al. 2002).

Similar to global literature, previous studies (Table 1) in China suggested that (1) few studies have been carried out in the humid region of southern China, (2) both increasing (Yang et al. 2014) and decreasing (Zhang et al. 2009, 2010; Chen et al. 2011; Fan and Thomas 2013) trends of ET_o were detected in different regions, and (3) changes in ET_o were affected not only by air temperature but also by other meteorological variables including WS, R_s, RH, absolute humidity (AH), and VPD (Cohen et al. 2002; Liu et al. 2010; Yin et al. 2010; Jhajharia et al. 2012; Zhao et al. 2015). Therefore, there is a need to study the long-term trend of ET_o and comprehensive influence of various climatic factors on ET_o in humid regions of southern China.

The Qinhuai River Basin (QRB) used for this case study has a subtropical climate typical of the Yangtze River Delta of southern China. The region is rapidly developing and has been facing chronic environmental challenges such as water pollution, drought, and flooding, and urban heat islands (Liu et al. 2013; Zhao et al. 2014; Zhou et al. 2014). Our previous study (Hao et al. 2015b) suggested that the rapid urbanization by converting paddy fields with water withdrawal for large-scale irrigation to impervious surface in this basin have altered the watershed hydrology through changes in ET. A further study on the climatic control on ET_o could help us to better understand environmental controls (i.e., climate and land use change) on actual ET and other watershed hydrological processes in this basin.

Based on previous studies of ET_o in the humid region, we proposed two hypotheses to guide our research: (1) ET_o has increased during 1961–2012 over the QRB and (2) in addition to the increased air temperature, other meteorological variables have influenced ET_o variations: the changes in R_s, WS, RH, AH, and VPD all contributed to ET_o variation. Therefore, this study aimed to: (1) estimate daily, seasonal, and annual ET_o over the QRB for the period of 1961–2012 with the FAO-56 P–M model; (2) determine the temporal trends of ET_o, eight key meteorological variables, radiometric and aerodynamic terms with the Mann–Kendall (MK) nonparametric test, Theil–Sen's estimator, and Cramer's test; and (3) identify the dominant climatic factors influencing ET_o at seasonal and annual scales by a detrending method.

METHODOLOGY

Study Area and Databases

The QRB is located in the southwest of Jiangsu Province (118°39′–119°19′E, 31°34′–32°10′N) (Figure 1) covering an area of 2,617 km^2 including Nanjing,

TABLE 1. The trends of ET_o and dominant meteorological variables in different basins of China.

Region	Locations	Periods	Trends of ET_o	Dominant meteorological variables	References
China	—	1971–2008	Decreased in 1971–2008	Declining WS and decreasing sunshine duration	Yin et al. (2010)
China	—	1960–2011	Decreased in 1960–1992	Before 1992: decrease in solar radiation in humid region; decrease in WS in arid and semiarid/semi-humid region	Zhang et al. (2013)
			Increased in 1993–2011	After 1992: rapidly increasing temperature in all three regions	
Yangtze River Basin	South	1960–2000	Decreased	Decrease in net total radiation and WS	Xu et al. (2006)
Yellow River Basin	North	1961–2006	Increased in the whole basin	Increasing air temperature and decreasing RH	Liu et al. (2010)
Jing River Basin	Northwest	1960–2005	Decreased in spring, summer, and winter	Spring, summer, and winter: decrease in WS	Xu et al. (2015)
			Increased in autumn	Autumn: increase in maximum temperature	
Taohe River Basin	Northwest	1981–2010	Increased	Increasing air temperature and net total radiation	Yang et al. (2014)
Hai River Basin	North	1960–2012	Decreased in 1960–1989 Increased in 1990–2012	Before 1989: decrease in solar radiation After 1989: global warming	Zhao et al. (2015)
Qinhuai River Basin	Southeast	1961–2012	Decreased in 1961–1987 Increased in 1988–2012	Before 1987: decrease in WS, solar radiation, and VPD After 1987: rapidly increasing VPD and increasing T_{max}	This study

Note: ET_o, reference evapotranspiration; WS, wind speed; RH, relative humidity; VPD, vapor pressure deficit.

Lishui, and Jurong cities. Paddy rice field, dry cropland, and urban area separately occupied 33%, 26%, and 24% of the basin (Figure 1). The QRB has experienced an urbanization boom during 1988–2009 (Du et al. 2012). By 2013, the built-up land has expanded to nearly one-fourth (655 km^2) of the whole basin (Figure 1). The QRB includes several cities with a population over 8 million and water demand for drinking water, irrigation, and industry use has placed great pressure on water resources management in this "water-rich" region. The annual precipitation over QRB was nearly 1,000 mm (Du et al. 2012) and it was higher than 800 mm which was considered to be the dividing line between semi-humid and humid regions in China.

Daily meteorological data from six standard weather stations in or around the QRB from 1961 to 2012 were provided by the China Meteorological Data Sharing Service System (http://data.cma.cn/) and Jiangsu Weather Bureau. Necessary variables to estimate ET_o included WS (m/s), RH (%), sunshine duration (n, hours), daily mean temperature (T_{mean}, °C), maximum and minimum temperature (T_{max} and T_{min}, °C). According to the "2004 Standard of Surface Meteorology Observation by the China Meteorology Administration," the WS, RH, sunshine duration, T_{mean}, T_{max}, and T_{min} were separately measured by the EL type electrical anemometer, hair hygrometer, bimetallic strip sunshine sensor, wet and dry bulb thermometer, maximum thermometer and minimum thermometer. The data preprocessing and quality control were carried out by the China Meteorology Administration. However, missing daily data were not gap-filled. In this study, there were just about 20 missing daily records at each station which represented about 0.1% of our study period (about 20,000 days). Therefore, we filled these missing daily data with the data of the nearby station. The Jiangning station did not have climate data after 2007, while the other five stations had complete meteorological data from 1961 to 2012. The QRB is dominated by paddy rice field, and the rice growing season is between May and October when flood irrigation is needed (Hao et al. 2015b). Accordingly, data were analyzed by six time periods: spring (March–May), summer (June–August), autumn (September–November), winter (December–February in the next year), and were summarized for the growing season and the entire calendar year.

FAO-56 P–M Model for Estimating ET_o

The FAO-56 P–M model has been widely used to estimate ET_o and was applicable to humid conditions (Allen et al. 1998; McMahon et al. 2013). This model can be expressed:

$$\mathrm{ET_o} = \frac{0.408\Delta(R_\mathrm{n} - G) + \gamma \frac{900}{T+273} U_2(e_\mathrm{s} - e_\mathrm{a})}{\Delta + \gamma(1 + 0.34U_2)}, \quad (1)$$

where Δ is the slope of the saturated vapor pressure curve (kPa/°C), R_n the net radiation (MJ/m^2/day), G the soil heat flux density (MJ/m^2/day) (zero on the daily scale), γ the psychrometric constant (kPa/°C), T the mean daily air temperature (°C), U_2 the mean daily WS at 2 m height (m/s), e_s the saturated vapor pressure (kPa), e_a the actual vapor pressure (kPa), and e_s–e_a the VPD (kPa). This model includes a radiometric term (R_o):

$$R_\mathrm{o} = \frac{0.408\Delta(R_\mathrm{n} - G)}{\Delta + \gamma(1 + 0.34U_2)} \quad (2)$$

and an aerodynamic term (A_o):

$$A_\mathrm{o} = \frac{\gamma \frac{900}{\mathrm{T}+273} U_2(e_\mathrm{s} - e_\mathrm{a})}{\Delta + \gamma(1 + 0.34U_2)} \quad (3)$$

Key radiation variables in P–M model were derived by following equations:

$$R_n = R_\mathrm{ns} - R_\mathrm{nl} \quad (4)$$

$$R_\mathrm{ns} = (1 - \alpha)R_\mathrm{s} \quad (5)$$

$$R_\mathrm{s} = \left(a + b\frac{n}{N}\right)R_\mathrm{a} \quad (6)$$

$$R_\mathrm{a} = \frac{1,440}{\pi} G_\mathrm{sc} d_\mathrm{r} \omega_\mathrm{s} \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_\mathrm{s}) \quad (7)$$

$$R_\mathrm{nl} = \sigma\left(\frac{T^4_{\mathrm{max},k} + T^4_{\mathrm{min},k}}{2}\right)(0.34 - 0.14\sqrt{e_\mathrm{a}}) \left(1.35\frac{R_\mathrm{s}}{R_\mathrm{so}} - 0.35\right), \quad (8)$$

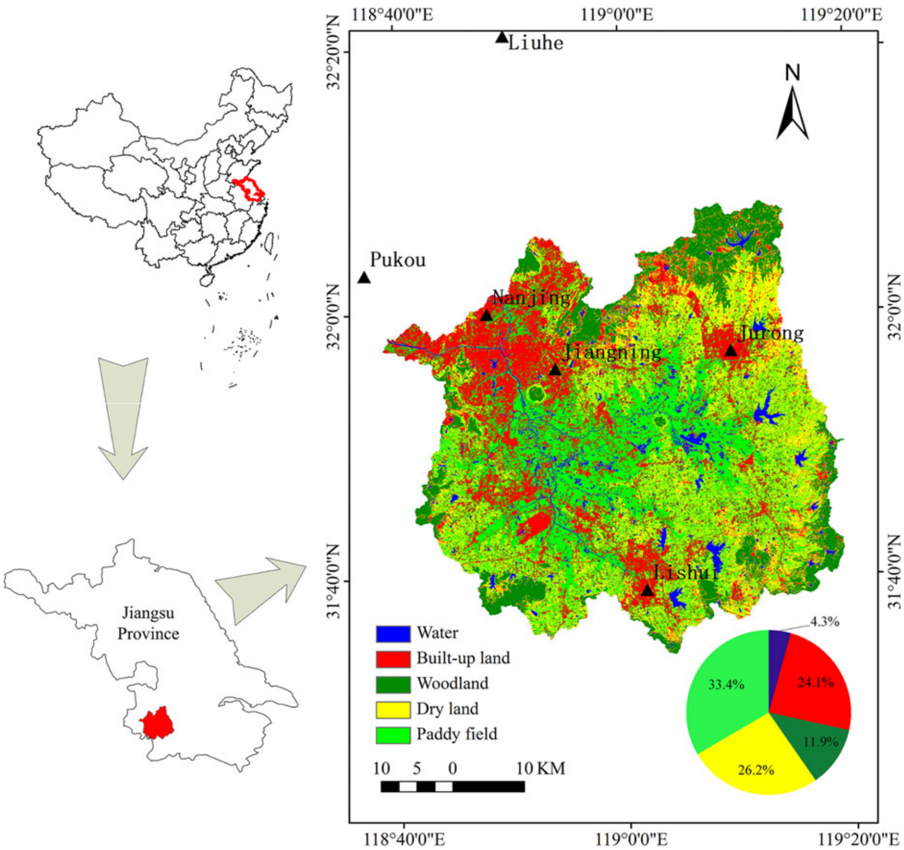

FIGURE 1. Watershed location, land use and land cover (2013), and weather stations in the Qinhuai River Basin (QRB). The insert pie chart indicates the proportion of five land use areas to total area.

where R_{ns} and R_{nl} are the incoming net short-wave and outgoing net long-wave radiation (MJ/m^2/day), α the albedo fixed as 0.23, R_s the solar radiation (MJ/m^2/day), n and N were the actual and maximum possible sunshine hours (h), respectively, R_a extraterrestrial radiation (MJ/m^2/day), G_{sc} the solar constant (0.08232 MJ/m^2/min), d_r inverse relative distance from earth-to-sun, ω_s the sunset hour angle (rad), ϕ latitude (rad), δ solar declination (rad), σ the Stefan–Boltzmann (4.903×10^{-9} MJ/m^2/day), $T_{max,k}$ and $T_{min,k}$ the maximum and minimum absolute temperature within 24 h (K), R_{so} the clear sky solar radiation (MJ/m^2/day), a and b the empirical coefficients of 0.25 and 0.5 (Allen et al. 1998).

Calculated R_s with the weather data was compared to the observed data at the Nanjing station to evaluate the accuracy (Figure 2). Results showed that there was a significant ($p < 0.05$) correlation between the calculated and measured R_s, with the correlation coefficient of 0.87. Additionally, the root-mean-square error of the calculated and observed R_s was 2.7 W/m/day. The statistics indicated that the method to compute R_s of the FAO-56 P–M model can be applied in our study area. Furthermore, this method has also been used in other regions within China (Liu et al. 2010; Yin et al. 2010; Shan et al. 2015; Irmak et al. 2012; Huo et al. 2013).

The VPD (kPa) is calculated as (Allen et al. 1998):

$$\mathrm{VPD} = e_s - e_a \quad (9)$$

where e_s (kPa) can be calculated from T_{max} and T_{min}:

$$e_s = \frac{e^0(T_{max}) + e^0(T_{min})}{2} \quad (10)$$

$$e^0(T_{max}) = 0.6108 \exp\left[\frac{17.27T_{max}}{T_{max} + 273.3}\right] \quad (11)$$

$$e^0(T_{min}) = 0.6108 \exp\left[\frac{17.27T_{min}}{T_{min} + 273.3}\right] \quad (12)$$

Finally, we computed e_a (kPa) with the e_s and measured daily mean RH:

$$e_a = e_s \times \mathrm{RH} \quad (13)$$

AH (g/m^3) was calculated with e_a:

$$\mathrm{AH} = c\frac{e_a}{T + 273.3}, \quad (14)$$

where c is a constant with a value of 217 and e_a is the actual vapor pressure (hPa) (Xie et al. 2014).

We examined the effects of eight climate variables (R_s, WS, RH, AH, VPD, T_{mean}, T_{max}, T_{min}), radiometric and aerodynamic terms on ET_o variation. R_s, controlled by sunshine hours and geographic location limits the amount of energy available to vaporize the water (Allen et al. 1998; Gong et al. 2006; Xu et al. 2006; Liu et al. 2010; Irmak et al. 2012; Gao et al. 2017). WS is an important variable that directly affects ET_o. RH represents the degree of moisture content of atmosphere, while AH indicates the weight of water vapor in one unit of moist air. VPD, determined as the difference between saturated vapor pressure and actual vapor pressure is directly related to atmospheric water demand (Novick et al. 2016).

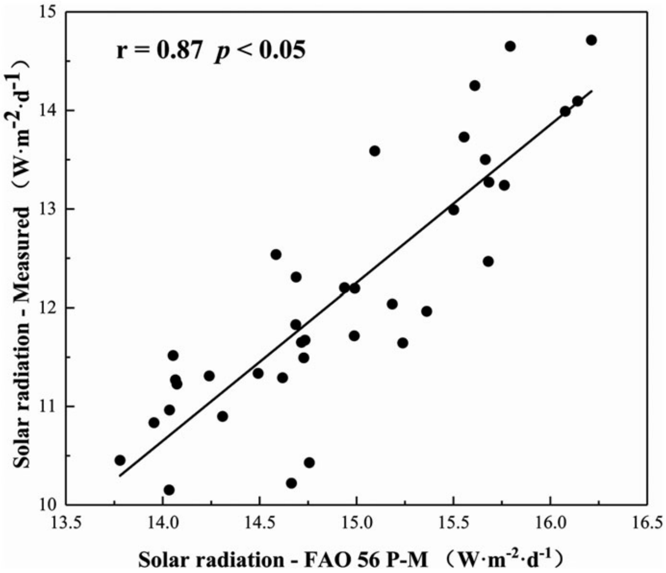

FIGURE 2. Solar radiation calculated with FAO-56 Penman–Monteith model compared to the measured solar radiation at Nanjing station.

MK Test

The nonparametric MK test (Mann 1945; Kendall 1975) was applied to examine the significance of the changing trends of climate variables and ET_o in some hydrological studies (Liu et al. 2010; Darshana et al. 2013; Li et al. 2013; Fan et al. 2016). The statistic S is calculated as

$$S = \sum_{k=1}^{n-1}\sum_{j=k+1}^{n} \mathrm{sgn}(X_j - X_k), \quad (15)$$

where X_j represents the sequential data values, n is the number of the dataset, and

$$\mathrm{sgn}(X_j - X_k) = \begin{cases} 1 & \text{if} X_j - X_k > 0 \\ 0 & \text{if} X_j - X_k = 0 \\ -1 & \text{if} X_j - X_k < 0 \end{cases}, \quad (16)$$

when n >10, S is approximately normally distributed with $E(S) = 0$, and variance of statistic S can be calculated by:

$$\mathrm{Var}(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{w=1}^{v} t_w(t_w-1)(2t_w+5)\right], \quad (17)$$

where v is the number of tied groups and t_w is number of data values in wth group.

The standard test statistic (Z) is:

$$Z = \begin{cases} \frac{s-1}{\sqrt{\mathrm{Var}(s)}} & \text{if} s > 0 \\ 0 & \text{if} s = 0 \\ \frac{s+1}{\sqrt{\mathrm{Var}(s)}} & \text{if} s < 0 \end{cases} \quad (18)$$

The null hypothesis $H0$ is rejected when $|Z| > Z_{1-\alpha/2}$, where $Z_{1-\alpha/2}$ is the standard normal deviation. $|Z| > 1.28$, 1.64, and 2.32 denotes the changing trends are significant at >90% ($p < 0.1$), 95% ($p < 0.05$), and 99% ($p < 0.01$), respectively.

Theil–Sen's Estimator

Theil–Sen's estimator method (Sen 1968; Hirsh et al. 1982) was used to estimate magnitudes of ET_o trends (Tabari et al. 2011; Darshana et al. 2013; Xu et al. 2015):

$$\beta = \mathrm{Median}\left(\frac{X_j - X_k}{j-k}\right),\ 1<k<j<n, \quad (19)$$

where β is the estimated magnitude of slopes of ET_o trends. $\beta > 0$ represents an increasing trend; $\beta < 0$ represents a decreasing trend.

Cramer's Test

Cramer's test is performed to examine the stability of a record in terms of a comparison between the overall mean of an entire record and the means of certain parts of the record (Türkes 1996; Zhang et al. 2013). This test statistic t_k is computed as:

$$t_k = \sqrt{\frac{n(N-2)}{N-n(1+\tau_{k)}^2}}\tau_k \quad (20)$$

$$\tau_k = \frac{\bar{x}_k - \bar{x}}{s},\ \bar{x}_k = \frac{1}{n}\sum_{i=k+1}^{k+n} x_i, \bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i \quad (21)$$

$\bar{x}$ and s are the mean and standard deviation of the entire period of N years, respectively, and $\bar{x}_k$ is the mean of the subperiod of n years to be compared with $\bar{x}$. The test statistic t_k is distributed as Student's t with ($N - 2$) degrees of freedom. The null hypothesis of no significant difference between the mean of a sub-period and the mean of a whole period is rejected with the two-tailed test for large values of $|t_k|$.

Detrending Method

Previous studies (Xu et al. 2006; Liu et al. 2010; Huo et al. 2013; Li et al. 2013) provided a simple and effective detrending method to quantify the impacts of changing meteorological variables on ET_o. This method includes three steps: (1) removing the changing trend of each variable to render them stationary, (2) recalculating ET_o with one detrended variable while keeping the other variables unchanged, and (3) comparing the recalculated ET_o with original ET_o. The contribution of changes in climatic factors to changes in ET_o can be quantified by an evaluating indicator R:

$$R = \sum_{i=1}^{m} \frac{\left(ET_o^o - ET_o^R\right)}{ET_o^o i}, \quad (22)$$

where ET_o^o and ET_o^R are original and recalculated ET_o, respectively, m is the length of the dataset. $R > 0$ denotes the change of this climatic factor has positive effects to the changes in ET_o; $R < 0$ denotes the change of this climatic factor has negative effects; and $R \approx 0$ denotes the change of this climatic factor leads to little impact on changes of ET_o. The larger value of $|R|$ denotes that the change of this climatic factor has a greater impact on the change of ET_o (Li et al. 2013).

RESULTS

Climatic Characteristics

Meteorological data from six standard weather stations around the watershed were used to characterize watershed-wide climate (Figure 3). The multiyear daily mean air temperature was 15.6°C and showed an increasing trend with 0.04°C/yr since 1987 (Figure 3c and Table 2). Mean annual precipitation was about 1,000 mm, 70% of which fell in the growing season (Figure 3a). Seasonal climate varied across

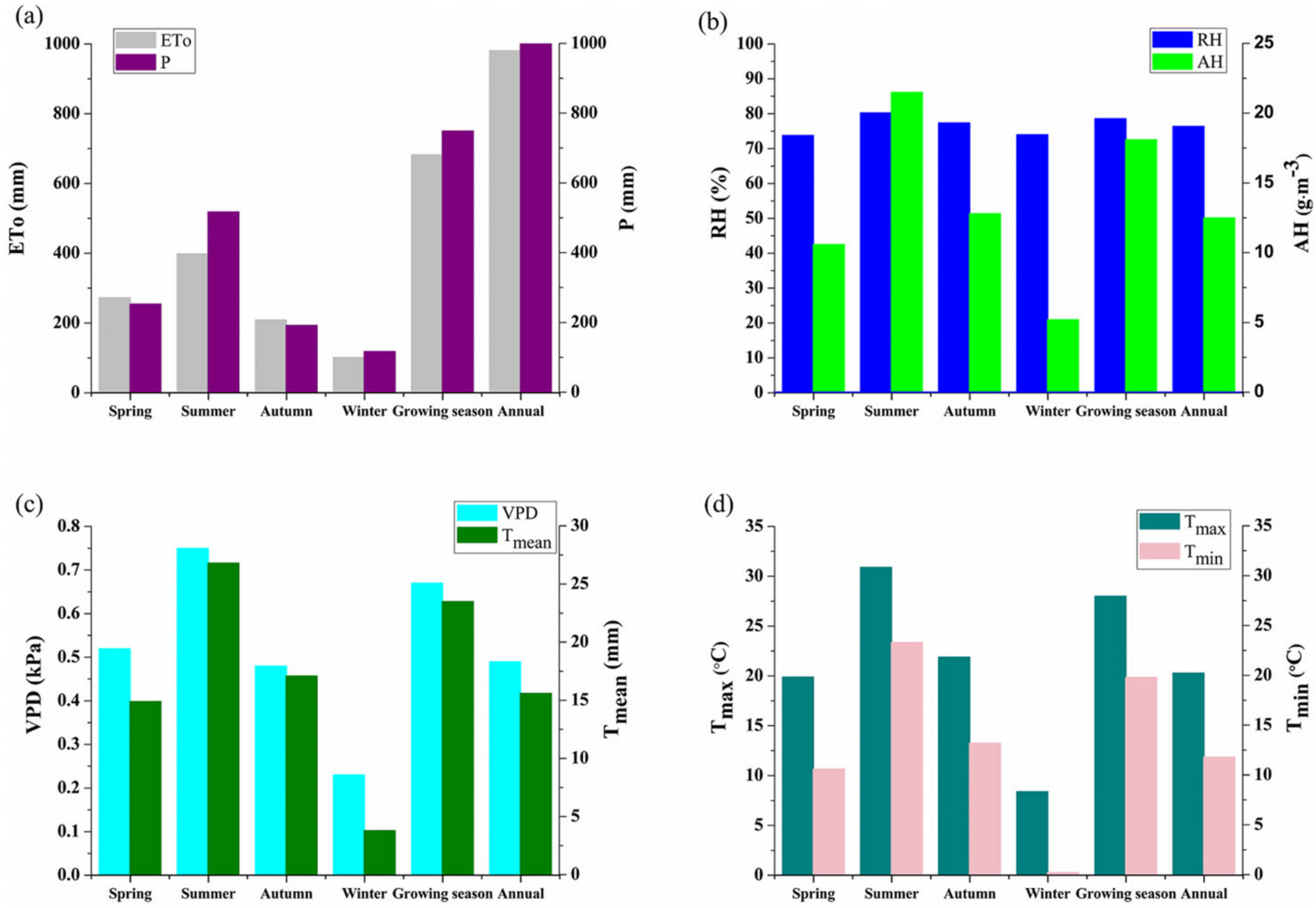

FIGURE 3. Basic meteorological information in QRB during 1961–2012. Bars in the figures represent the average based on the six sites and the 52 years of data. (a) ET_o and precipitation (P); (b) relative humidity (RH) and absolute humidity (AH); (c) VPD and mean temperature (T_{mean}); and (d) maximum temperature (T_{max}) and minimum temperature (T_{min}).

variables where ET_o was the highest in the summer (nearly 400 mm) and dropped to nearly 100 mm in the winter (Figure 3a); precipitation in QRB peaked in summer (Figure 3a) mainly influenced by Asian monsoons (Liang et al. 2010); summer RH and AH were both higher than those in other seasons (Figure 3b); VPD reached the peak in summer and stayed at the lowest in winter (Figure 3c).

Trends of Climatic Variables in 1961–1987 and 1988–2012

Results from the Cramer's test for seasonal and annual climatic variables showed that the abrupt change mostly occurred in 1987. Additionally, the changing trends of most climatic variables examined by MK test during 1961–1987 and 1988–2012 were also opposite (Table 2). R_s increased by 0.013 and 0.007 MJ/m^2/day/yr for spring and autumn during 1961–1987. For the other four time periods, the R_s decreased from -0.061 MJ/m^2/day/yr in summer to -0.021 MJ/m^2/day/yr in winter (Table 2). WS was the only variable which showed significantly decreasing trends ($p < 0.05$) at both seasonal and annual scale during 1961–1987 with the slopes ranging from -0.034 (winter) to -0.014 m/s/yr (summer) (Table 2). For the climate variables indicating the air humidity, the RH and VPD only showed significantly changing trends ($p < 0.05$) in summer with the slopes of 0.104%/yr and -0.005 kPa/yr, respectively (Table 2). The AH showed insignificantly decreasing trends at both seasonal and annual scale with the slopes between -0.029 g/m^3/yr in summer and -0.008 g/m^3/yr in winter (Table 2). This indicated that there was minor change of air humidity in all six time periods except for the summer in which the air humidity showed an increasing trend. T_{mean}, T_{max}, and T_{min} all showed decreasing trends at both seasonal and annual scale with the highest slopes in summer with

TABLE 2. Trends of key meteorological variables, radiometric term, and aerodynamic term in QRB during 1961–1987 and 1988–2012.

Periods	Variables	Spring	Summer	Autumn	Winter	Growing season	Annual
1961–1987	R_s (MJ/m^2/day)	0.013	−0.061*	0.007	−0.021	−0.031	−0.027*
	WS (m/s)	−0.031***	−0.014*	−0.032***	−0.034***	−0.025***	−0.027***
	RH (%)	−0.103	0.104*	0.035	−0.03	0.071	0.033
	AH (g/m^3)	−0.012	−0.029	−0.012	−0.008	−0.013	−0.013
	VPD (kPa)	0.001–	−0.005**	−0.001	0.001	−0.003	−0.002
	T_{mean} (°C)	−0.009	−0.043*	−0.01	−0.003	−0.015	−0.013
	T_{max} (°C)	−0.02	−0.054**	−0.019	−0.018	−0.026$^+$	−0.029*
	T_{min} (°C)	−0.007	−0.029*	−0.008	−0.007	−0.018	−0.011
	R_o (mm/day)	0.5$^+$	−0.96$^+$	0.23	0.06	−0.45	−0.27
	A_o (mm/day)	−0.45	−1.1**	−0.75**	−0.36*	−1.89**	−2.86***
1988–2012	R_s (MJ/m^2/day)	0.048$^+$	−0.073$^+$	−0.051*	−0.02	−0.049$^+$	−0.018
	WS (m/s)	0.002	0.001	0.002	0.004	−0.001	0.002
	RH (%)	−0.52***	−0.31***	−0.20*	−0.28***	−0.33***	−0.38***
	AH (g/m^3)	−0.026	−0.046*	−0.006	−0.024$^+$	−0.030$^+$	−0.025
	VPD (kPa)	0.014***	0.014***	0.007***	0.003*	0.013***	0.010***
	T_{mean} (°C)	0.079**	0.038$^+$	0.058**	−0.014	0.045**	0.039*
	T_{max} (°C)	0.114**	0.037$^+$	0.03	−0.028	0.048**	0.038$^+$
	T_{min} (°C)	0.056$^+$	0.045*	0.084**	0.001	0.055***	0.041*
	R_o (mm/day)	0.86*	−1.19$^+$	−0.25$^+$	−0.18	−1.01	−0.82
	A_o (mm/day)	1.98***	1.58**	0.81**	0.6**	2.7***	4.85***

Note: Meteorological variables are solar radiation (R_s), radiometric term (R_o), and aerodynamic term (A_o).
***, **, *, and $^+$ means the significance level of 0.001, 0.01, 0.05, and 0.1, respectively.

−0.04, −0.05, and −0.03°C/yr, respectively ($p < 0.05$) and lowest slopes in winter with −0.003, −0.018, and −0.007°C/yr, respectively (Table 2). The radiometric term only showed significantly changing trends in spring and summer ($p < 0.1$) with the slopes of 0.5 and −0.96 mm/day/yr, respectively (Table 2). However, except for the spring, the aerodynamic term decreased significantly ($p < 0.05$) in the other five time periods ranging from −2.8 mm/day/yr at annual scale to −0.36 mm/day/yr in winter during 1961–1987 (Table 2).

During 1988–2012, R_s decreased at both seasonal and annual scale except for the spring in which R_s increased by 0.048 MJ/m^2/day/yr ($p < 0.1$) (Table 2). In contrast to that in 1961–1987, the WS did not change significantly at both seasonal and annual scale during 1988–2012 (Table 2). Climate variables related to air humidity had greater changes in 1988–2012 when compared to that in 1961–1987 (Table 2). Specifically, the RH decreased significantly ($p < 0.05$) at both seasonal and annual scale with the range from −0.52%/yr (spring) to −0.2%/yr (autumn) (Table 2). Conversely, VPD increased from 0.003 kPa/yr in winter ($p < 0.05$) to 0.014 kPa/yr in both spring and summer ($p < 0.05$) during 1988–2012 (Table 2). The AH decreased at both seasonal and annual scale but only significant ($p < 0.1$) in summer, winter, and the growing season (Table 2). Corresponding to the global warming, the air temperature (T_{mean}, T_{max}, and T_{min}) increased significantly ($p < 0.05$) in all six time periods except for winter in which the air temperature had minor changes (Table 2). We also found that the T_{mean} and T_{max} had the highest increasing slopes in spring (0.079 and 0.114°C/yr) and the T_{min} had the highest increasing slope in autumn (0.084°C/yr) (Table 2). Similar to the R_s variation in 1988–2012, the radiometric term increased by 0.86 mm/day/yr in spring ($p < 0.05$) and decreased in the other five time periods with the slopes between −1.19 mm/day/yr in summer ($p < 0.1$) and −0.18 mm/day/yr in winter (Table 2). Conversely, the aerodynamic term in 1988–2012 increased significantly ($p < 0.05$) at both seasonal and annual scale with the range from 0.6 mm/day/yr in winter to 4.85 mm/day/yr at the annual scale (Table 2).

Trends of ET_o during 1961–1987 and 1988–2012

We found that the annual ET_o over QRB decreased during 1961–1987, then increased during 1988–2012 (Table 3). Slopes of these annual trends were both higher than 3 mm/yr. The multiyear average ET_o in 1961–1987 and 1988–2012 were both close to 1,000 mm with about 70% occurring in the growing season (Table 3). The growing season ET_o exhibited a decreasing rate at −2.53 mm/yr in 1961–1987 ($p < 0.05$) and increased by 1.09 mm/yr in 1988–2012 (Table 3). In four seasons, the mean values of ET_o during 1961–1987 were very close to those in 1988–2012, respectively (Table 3). Summer ET_o in 1961–1987 had the highest decreasing slope with

TABLE 3. Mean seasonal and annual ET_o estimated by FAO-56 Penman–Monteith model; trends of seasonal and annual ET_o obtained through Mann–Kendall test during 1961–1987 and 1988–2012.

	1961–1987			1988–2012		
Season	**ET_o (mm)**	**Trend**	**β (mm/yr)**	**ET_o (mm)**	**Trend**	**β (mm/yr)**
Spring	266	↓	−0.04	280	↑**	2.55
Summer	404	↓**	−2.05	391	↑	0.16
Autumn	206	↓	−0.57	211	↑+	0.38
Winter	102	↓+	−0.37	100	↑*	0.56
Growing season	685	↓*	−2.53	679	↑	1.09
Annual	980	↓**	−3.82	982	↑**	3.16

Note: β is the estimated magnitude of slopes of ET_o trends; $\beta > 0$ represents an increasing trend (↑); $\beta < 0$ represents a decreasing trend (↓). ***, **, *, and + means the significance level of 0.001, 0.01, 0.05, and 0.1, respectively.

−2.05 mm/yr ($p < 0.05$) (Table 3). Spring conditions produced an increasing trend as well as the highest rate of ET_o during 1988–2012 with the slope of 2.55 mm/yr ($p < 0.05$) (Table 3).

Original and Detrended Meteorological Variables at the Annual Scale

In 1961–1987, only the original RH showed an increasing trend which caused a lower detrended RH at the annual scale (Figure 4a). The biggest difference between original annual and detrended annual data was observed in WS in 1961–1987 (Figure 4b). In 1988–2012, the original annual RH, R_s, and AH showed negative trends which caused the higher detrended results (Figure 4a,4c,4d). Conversely, the other five original variables in 1988–2012 all showed positive trends which caused the lower detrended results (Figure 4b,4e–4h). We noticed that the differences between original variables of annual RH and VPD, and detrended annual RH and VPD were much larger than the other variables during 1988–2012. Based on the example of annual data (Figure 4) and the trend of each original meteorological variable (Table 2), we could distinguish the differences between each original and detrended meteorological variable at the seasonal scale.

Contributions of Climatic Variables to Trends of ET_o at the Annual Scale

The original annual ET_o and recalculated annual ET_o with eight detrended variables were presented as an example to show the differences between the two datasets (Figure 5). During 1961–1987, only the recalculated annual ET_o with detrended AH was lower than the original ET_o (Figure 5a), while recalculated annual ET_o with the other meteorological variables were all larger (Figure 5a–5d). The changes of R_s, WS, AH, and VPD had greater contributions to changes of ET_o at the annual scale during 1961–1987 (Figure 5a–5c). In 1988–2012, only the recalculated annual ET_o with detrended R_s was larger than the original annual ET_o (Figure 5f). The biggest differences were found between original annual ET_o and the recalculated annual ET_o with detrended RH and VPD (Figure 5e,5g). This indicates that changes of RH and VPD in 1988–2012 had the greatest influences on changes of ET_o, while changes of T_{mean} had the lowest effects at the annual scale.

Contributions of Climatic Variables to Trends of ET_o at the Seasonal Scale

During 1961–1987, the effects of decreased R_s and three temperature variables (T_{min}, T_{max}, and T_{mean}) were counterbalanced by the effects of changes in the other four variables, leading to little changes of ET_o in the spring (Figure 6a). For summer, decreased R_s, VPD, and increased RH were the dominant factors on the decreased ET_o (Figure 6b). For autumn and winter, the most likely causative factor was the decreased WS (Figure 6c,6d). The negative effects of decreased R_s, WS, VPD, and increased RH would offset the positive effect of decreased AH and then led to the decreased ET_o in the growing season and the whole year (Figure 6e,6f). In general, decreased R_s, VPD, and increased RH mainly caused the decreased ET_o in summer, while decreased WS was the main reason for decreased ET_o in autumn and winter during 1961–1987. For spring, the effects of different meteorological variables offset each other and led to little changes of ET_o. Compared to the four seasons, the decreased ET_o was greatly affected by more meteorological variables including R_s, WS, VPD, RH, and T_{max} in the growing season and whole year during 1961–1987 (Figure 6).

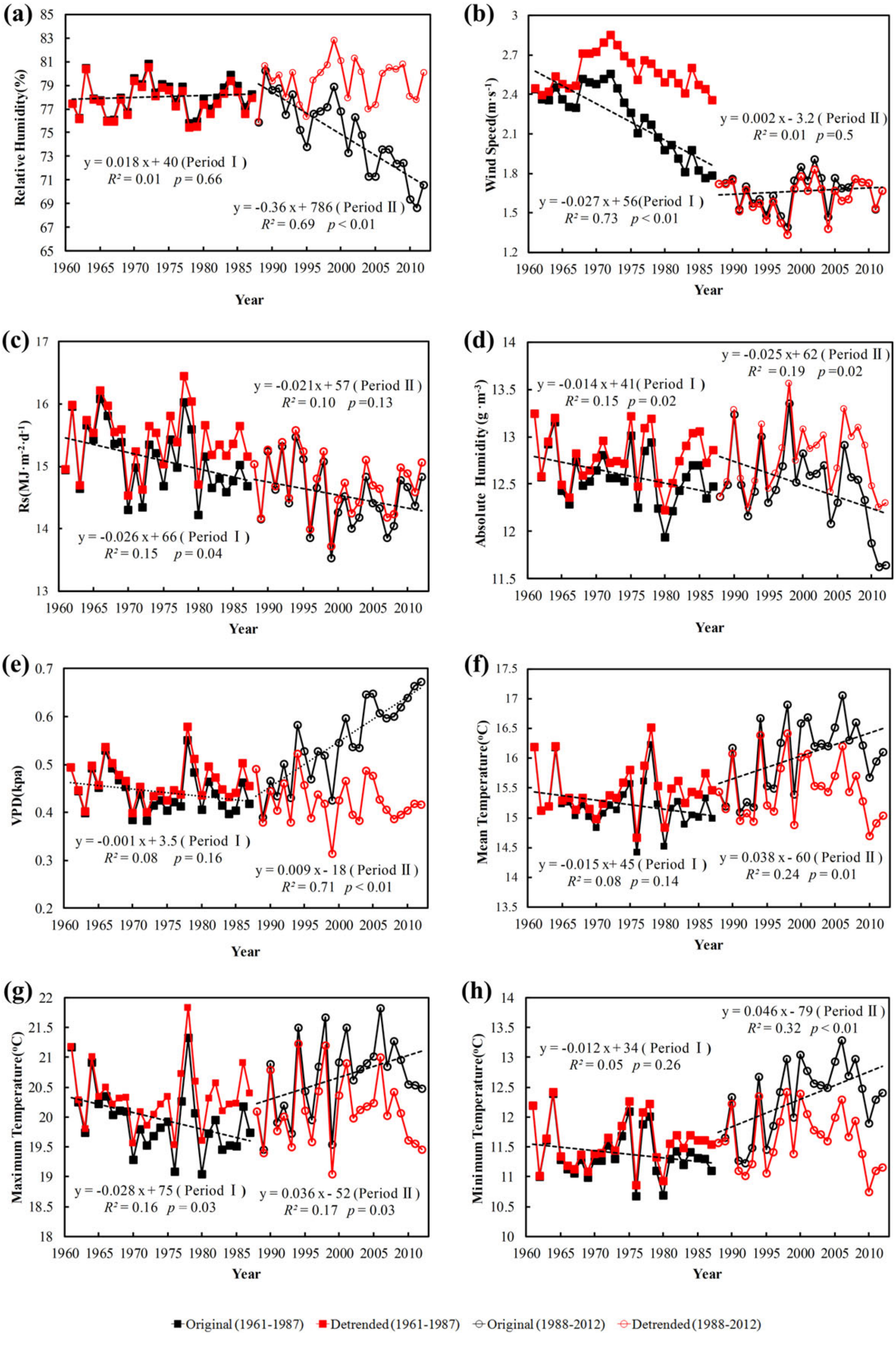

FIGURE 4. The annual original and detrended meteorological variables. (a) RH; (b) WS; (c) R_s; (d) AH; (e) VPD; (f) T_{mean}; (g) T_{max}; and (h) T_{min} for QRB by using detrending method (Period I represents 1961–1987 and Period II represents 1988–2012).

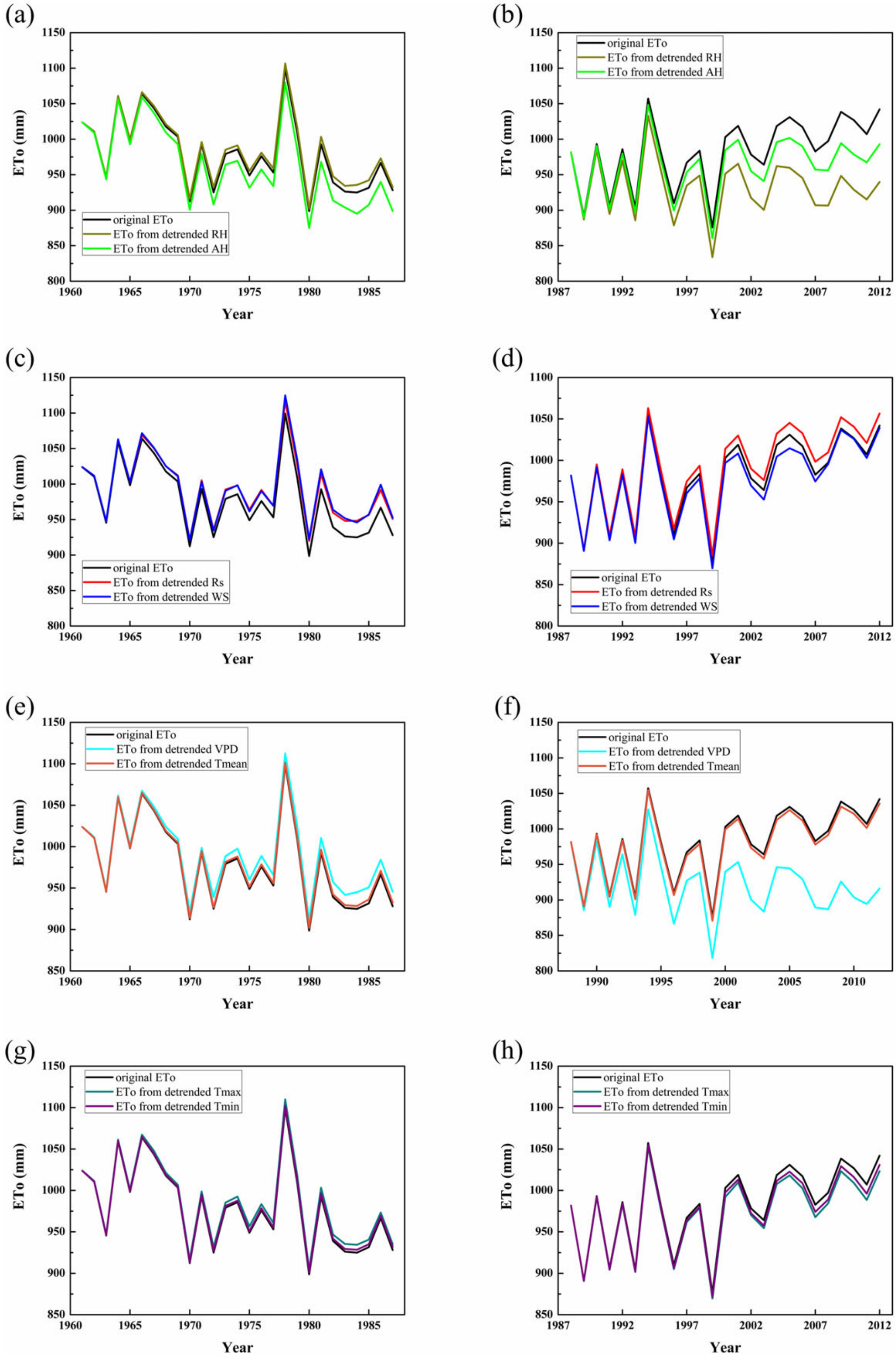

FIGURE 5. The original and recalculated annual ET_o for QRB with detrended meteorological variables during 1961–2012. (a, e) RH and AH; (b, f) R_s and WS; (c, g) VPD and T_{mean}; (d, h) T_{max} and T_{min}.

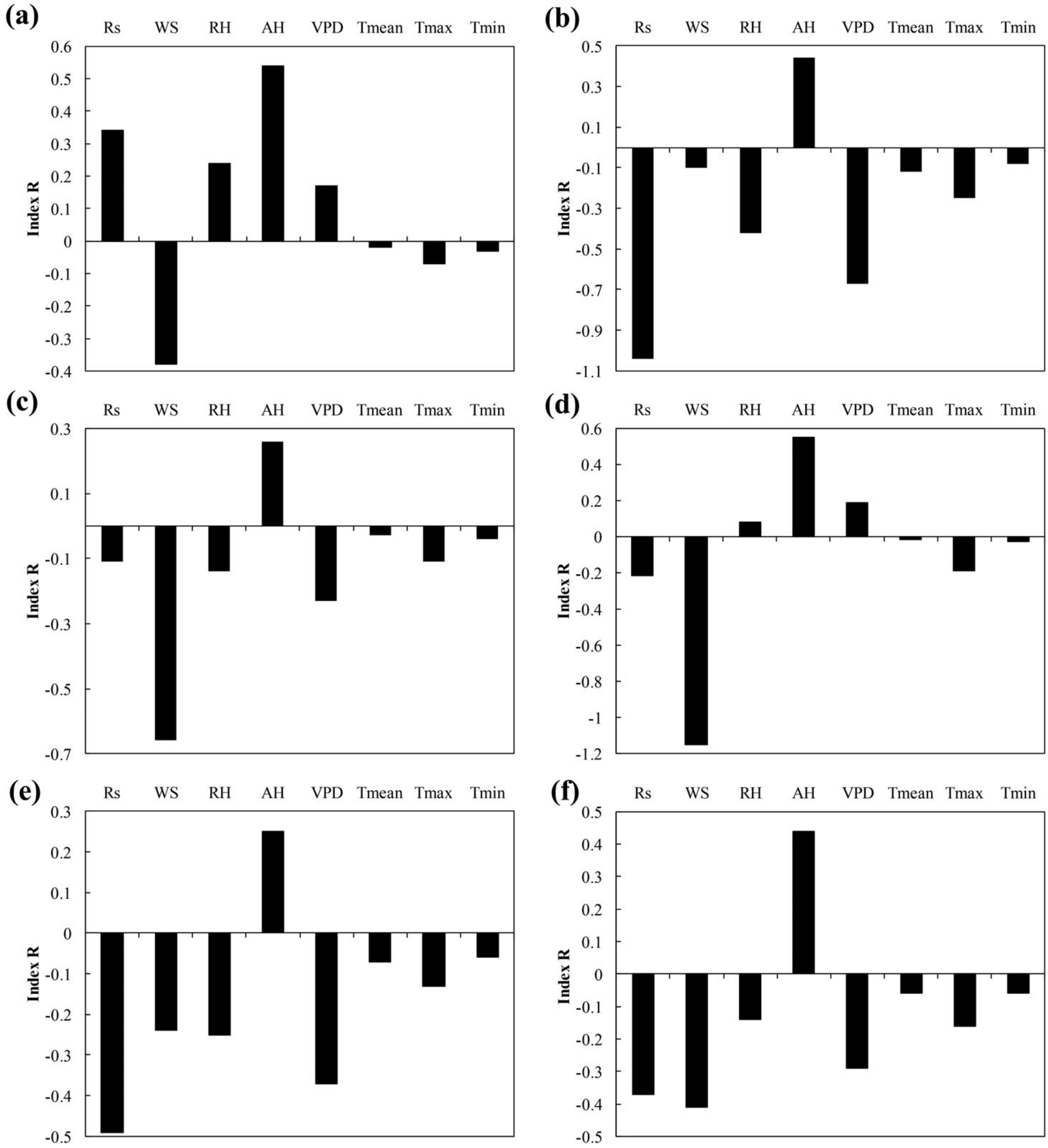

FIGURE 6. Comparisons of indicator R for identifying the contributions of trends in meteorological variables to trends in ET_o in (a) spring; (b) summer; (c) autumn; (d) winter; (e) growing season; and (f) annual during 1961–1987. An evaluating indictor R was constructed to quantify the contribution of climatic variables to ET_o trends. Positive R values indicate positive effects and negative values indicate negative effects; the greater of the absolute R values indicate greater contributions to changes in ET.

During 1988–2012, decreased RH and increased VPD were the main factors for the positive trend of ET_o in the spring (Figure 7a). For summer and autumn, positive effects of changes in RH and VPD offset the negative effect of changes in R_s, leading to the increased ET_o during 1988–2012 (Figure 7b,7c).

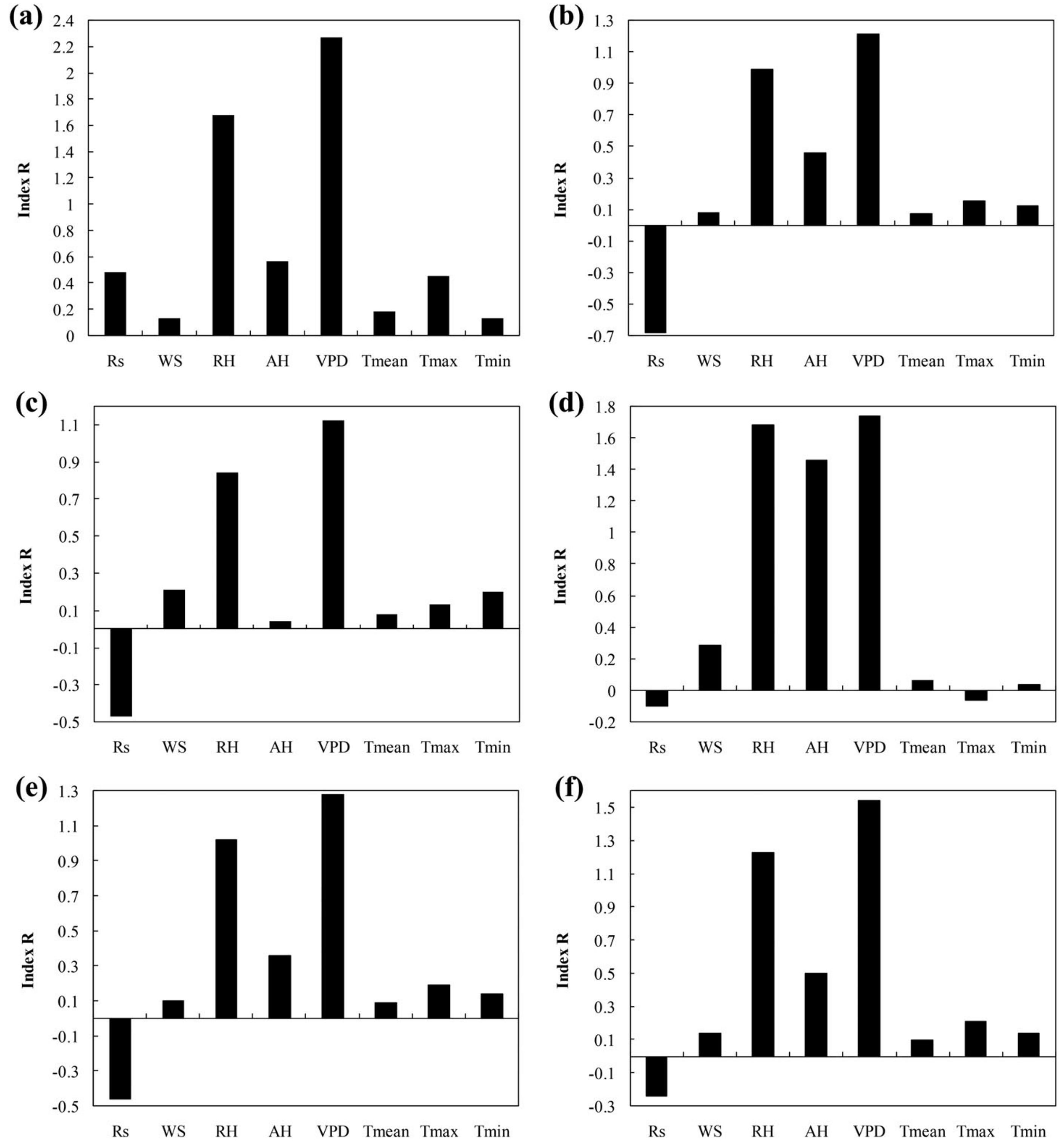

FIGURE 7. Comparisons of evaluating indicator R for identifying the contributions of trends in meteorological variables to trends in ET_o in (a) spring, (b) summer, (c) autumn, (d) winter, (e) growing season, and (f) annual during 1988–2012. Positive R values indicate positive effects and negative values indicate negative effects; the greater of the absolute R values indicate greater contributions to changes in ET_o.

In winter, changes of RH, AH, and VPD had the greatest impacts and resulted in the positive trend of ET_o (Figure 7d). The increased ET_o in the growing season and the whole year were mainly caused by the decreased RH and increased VPD (Figure 7e,7f). Compared to the effects of changes of RH and VPD, the decreased AH and increased air temperature influenced the ET_o variation to a lesser extent in the growing season and the whole year during 1988–2012. In general, increased VPD and decreased RH were the most influential factors for positive trends of ET_o at both seasonal and annual scale during 1988–2012 (Figure 7).

Contributions of Radiometric and Aerodynamic Terms to the Trends of ET_o

During 1961–1987, the positive effect of radiometric term was offset by the negative effect of aerodynamic term and caused the little change of ET_o in spring (Figure 8a). For summer, the decreased radiometric and aerodynamic terms both led to the decreasing trend of ET_o during 1961–1987 (Figure 8a). In autumn and winter, the negative effect of aerodynamic term offset the positive effect of radiometric term and resulted in the decreased ET_o (Figure 8a). The decreased ET_o rates in the growing season and the entire year were mainly caused by the decrease in the aerodynamic term during 1961–1987 (Figure 8a). The great positive effect of aerodynamic term was the dominant factor on the increased ET_o for both seasonal and annual scale during 1988–2012. The increased radiometric term was also an important influencing factor in spring (lower than the increased aerodynamic term), while there was little impact of the changed radiometric term in the other five periods during 1988–2012 (Figure 8b).

DISCUSSION

Temporal Trends of Meteorological Variables

Generally speaking, R_s showed decreasing trends in the entire study period (Table 2 and Figure 4c), which is consistent with some previous studies (Liu et al. 2010; Yin et al. 2010; Tabari et al. 2011; Jhajharia et al. 2012; Li et al. 2013; Xu et al. 2015). Irmak et al. (2012) attributed this feature to the increase in cloud cover and precipitation. The increase in atmospheric turbidity induced by air pollution and dust storms could also reduce R_s in China (Liu et al. 2004; Zhang et al. 2004).

A decrease in WS was observed over QRB during 1961–2012 (Table 2). A global decrease in terrestrial WS has also been observed (McVicar et al. 2012). In China, it is believed that a decline of pressure gradient, climate warming, and decreasing monsoon circulation commonly reduce atmospheric circulation and WS (Zhang et al. 2009, 2014). Additionally, the urbanization over QRB (Rui et al. 2011; Du et al. 2012; Hao et al. 2015b) may cause the negative effects on the WS variation (Li et al. 2018).

The decrease in RH that we found during 1988–2012 is consistent with global observations (Simmons

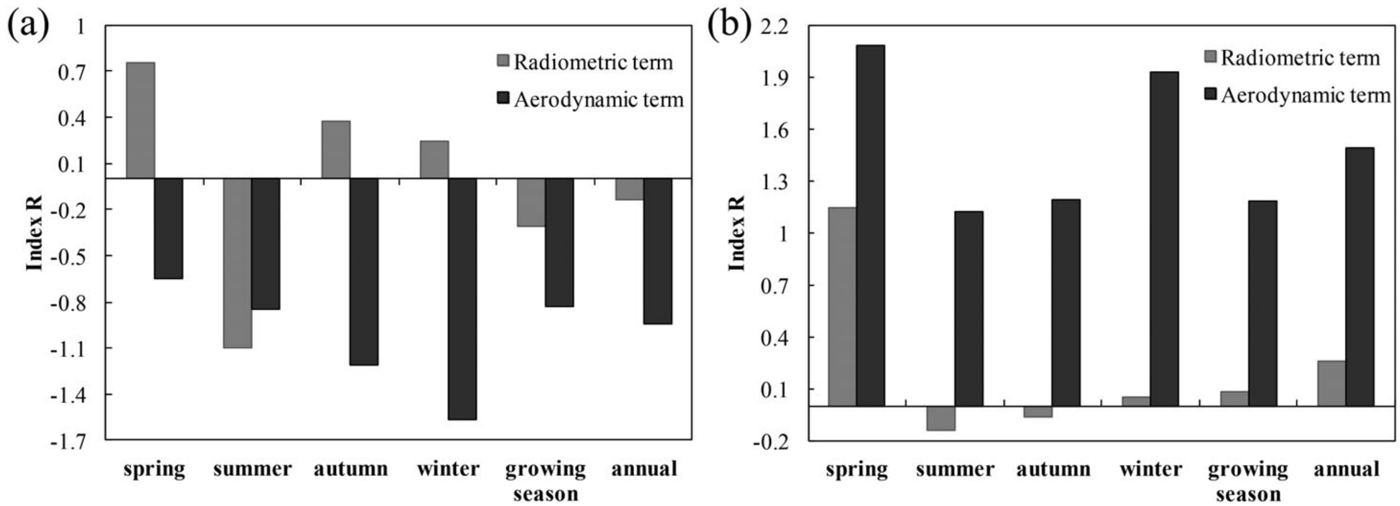

FIGURE 8. Comparisons of evaluating indicator R for identifying the contributions of variations in radiometric and aerodynamic terms to the variations of ET_o in different seasons during (a) 1961–1987 and (b) 1988–2012. An evaluating indictor R was constructed to quantify the contribution of climatic variables to ET_o trends. Positive R values indicate positive effects and negative values indicate negative effects; the greater of the absolute R values indicate greater contributions to changes in ET_o.

et al. 2010). Simmons et al. (2010) reported that the reduction in RH over land was due to the limited moisture from ocean, where evaporation has been limited by sea surface temperatures that have not risen in concert with temperatures over land. On the regional scale, RH was negatively correlated with the rapid warming (Van Wijngaarden and Vincent 2005; You et al. 2015) and positively correlated with the change in precipitation (Jin et al. 2009). Moreover, the rapid urbanization over QRB (Rui et al. 2011; Du et al. 2012; Hao et al. 2015b) reduced green spaces and increased surface runoff (Ying et al. 2007; Wypych 2010). Hao et al. (2015b) also found the loss of extensive paddy rice field which would lead to the decreased actual ET. These hydrologic changes limited the moisture of evaporation and then reduced the RH in this basin. A recent study suggests that urban dry island, a decline of air humidity and increase in VPD, was common in the lower Yangtze River Basin (Hao et al. 2018b).

During our study period, AH presented a negative trend over QRB (Table 2), which was similar to the situation in Guizhou province of southwest China (Han et al. 2016). However, Xie et al. (2014) observed the AH increased during 1951–2002 in Haihe River Basin in the plain region of northern China. Jiang et al. (2015) observed two change points in the variation of AH during 1960–2011 in the northern and southern regions of Qinling Mountains. The causes of the AH variation appear to be complex and further studies are needed over this basin.

The VPD increased from 1988 to 2012 in the QRB (Table 2). An increase in VPD was also reported globally by Matsoukas et al. (2011) who suggested that global warming was an important factor for increased VPD. On a regional scale, increased VPD was also observed in Bet Dagan, Israel in summer and autumn months (Cohen et al. 2002) and at a few sites in northeastern India (Jhajharia et al. 2012). In the Platte River Basin located in the U.S., Irmak et al. (2012) observed an increase in VPD and reported that the increased VPD was correlated strongly with the air temperature and precipitation. In our study basin, the increase in VPD was found to be the most important controlling factor in the changes of ET_o during 1988–2012. The increase in VPD was attributed to two reasons: (1) the increase in saturated vapor pressure (e_s) which was due to the warming trends and (2) the decreased actual vapor pressure (e_a) mainly induced by the inhibited evaporation and transpiration processes which were related to the rapid urbanization (Wypych 2010).

The warming trend (Table 2) in our study area was consistent with the climate trend in the Yangtze River Delta (Cui et al. 2008), northern and southern regions of Qinling Mountains (Zhou et al. 2011), Jing River Basin (Xu et al. 2015), and China as a whole (Han et al. 2013). Increasing trends of air temperature had also been found in other parts of the world (Tabari and Talaee 2011; Irmak et al. 2012; Jhajharia et al. 2012; Darshana et al. 2013). Previous studies attributed the increased air temperature to several reasons: global warming, increased greenhouse gases in the atmosphere (Soltani and Soltani 2008), and expanded cloudiness (Darshana et al. 2013). Moreover, urbanization and industrialization were considered to be a causation for the increase in temperature (Pielke 2005; Cui et al. 2008; Tabari and Talaee 2011). Therefore, we believed that the warming trend was also impacted by the rapid urbanization in QRB that was located in the Yangtze River Delta with the highest degree of urbanization in China (Gu et al. 2011).

Temporal Trends and Change Points of ET_o during 1961–2012 at the Annual Scale

Most similar studies in China have been conducted in water-shortage areas of northern China (Table 1). Most such studies in China and elsewhere showed a continuous unidirectional change in ET_o (Cohen et al. 2002; Xu et al. 2006, 2015; Liu et al. 2010; Yin et al. 2010; Tabari et al. 2011; Irmak et al. 2012; Jhajharia et al. 2012; Darshana et al. 2013; Yang et al. 2014; Shan et al. 2015; Gao et al. 2017). However, in recent years, some researchers found that the ET_o first decreased and then increased, with the change point in 1989 in Hai River Basin of northern China (Zhao et al. 2015), in 1983 in the arid inland region of northwestern China (Huo et al. 2013), and in 1992 in China as a whole (Zhang et al. 2013). Different from these studies, our study focused on the humid region of southern China. The change point of annual ET_o in 1987 was later than that (1983) found in the arid inland region in northwest of China but earlier than that (1992) in China as a whole. This was caused by the different dominant meteorological variables in different periods (Fan et al. 2016). Zhang et al. (2013) and Zhao et al. (2015) both suggested that the decrease in R_s led to the decreased annual ET_o in the first time period and the increase in air temperature was the main reason for the increased annual ET_o in the second period. However, in addition to the decreased R_s, we also found the decrease in WS contributed to the decreased annual ET_o during 1961–1987 over QRB (Figures 5 and 6f). The increase in annual ET_o during 1988–2012 were dominated by the increase in VPD rather than the air temperature over QRB (Figures 5 and 7f).

Contributions of Meteorological Variables to ET_o Trends at Seasonal and Annual Scales

Many studies found a decreased ET_o under a warming climate (Table 1). In contrast, we found the ET_o followed closely the air temperature variation in this study (Table 2 and Table 3). Our analysis indicated that ET_o was driven not only by air temperature but also by other meteorological variables in both the periods, 1961–1987 and 1988–2012. During the first period, decreased WS was found to be the most influential factor causing negative effects on ET_o in spring, autumn, winter, and the whole year (Figure 6a,6c,6d,6f). This was consistent with previous studies (Chen et al. 2006; Yin et al. 2010; Jhajharia et al. 2012; Darshana et al. 2013; Li et al. 2013; Xu et al. 2015). The most influential factor in the changes of ET_o was decreased R_s in summer and growing season (Figure 6b,6e), which was consistent with studies in Yunnan province of southwestern China (Fan and Thomas 2013), and subtropical and tropical regions in China (Yin et al. 2010). Decreased VPD and increased RH were also important influencing factors contributing to the decreased ET_o in summer and growing season during 1961–1987 (Figure 6b,6e). The increased RH was also found to contribute to the decreased ET_o in Tibetan Plateau for a study period before 2000 (Chen et al. 2006).

During 1988–2012, the positive trends of seasonal and annual ET_o were all dominated by the decreased RH and increased VPD (Figure 7). This was different from previous studies which reported the increase in air temperature was the main reason for the increased ET_o in the recent three decades (Zhang et al. 2013; Yang et al. 2014; Zhao et al. 2015). Moreover, for the humid region of southern China in a longer period (>40 years), researchers found the decreased ET_o and attributed this to the decrease in R_s and WS (Xu et al. 2006; Fan et al. 2016). Similar to our finding, some researchers reported that the decrease in RH contributed to the increased ET_o in the Yellow River Basin (Liu et al. 2010), Upper Heihe River Basin (Li et al. 2013), and west half of Iran (Tabari et al. 2011). However, these papers conducted their studies in the arid region and did not consider the impacts of changes of VPD which was directly related to the atmospheric demand. Our study indicated that increased VPD was an important factor to explain the increased ET_o over the QRB in the humid region of southern China.

The FAO-56 P–M model, as the most reliable method to estimate reference ET, incorporates both radiometric and aerodynamic terms (Gong et al. 2006; Xu et al. 2006; Rim 2009; Jhajharia et al. 2012). In addition to focus on the effects of climatic variables on ET_o variation (Liu et al. 2010; Yin et al. 2010; Tabari et al. 2011; Irmak et al. 2012; Jhajharia et al. 2012; Darshana et al. 2013; Zhang et al. 2013; Yang et al. 2014; Shan et al. 2015; Xu et al. 2015; Zhao et al. 2015; Fan et al. 2016; Gao et al. 2017), we also studied the effects of radiometric and aerodynamic terms on ET_o variation. We found that the variation of aerodynamic term was the dominant factor on the ET_o variation in both 1961–1987 and 1988–2012 (Figure 8). We also considered that the sharp decrease in WS led to the decreased aerodynamic term and then caused the decreased ET_o in 1961–1987. However, the increase in ET_o during 1988–2012 was caused by the increased aerodynamic term which was mainly induced by the increased VPD.

Implication of Increasing VPD and ET_o for Agricultural Water Management

Understanding water vapor distribution under climate change and an urbanizing environment is important to quantify altered hydrological processes. Most existing studies on water vapor focus on analyzing the surface RH (Van Wijngaarden and Vincent 2005; Vincent et al. 2007; Simmons et al. 2010). However, Novick et al. (2016) proposed that atmospheric demand for water is directly related to the VPD which also affects the surface conductance and hence ET. In our study, we found a sharp increase in VPD after 1987, which caused an increase in ET_o. Therefore, combined with high crop coefficients (i.e., ET/ET_o ratio), the crop water demand in growing seasons would increase with the rise in ET_o in the study region (Vu et al. 2005; Liu et al. 2010). In dry seasons (i.e., spring and winter) when there is limited precipitation over southern China, increased crop water demand would aggravate water shortage and may lead to serious adverse influences on food production (Fan et al. 2016). Wang et al. (2017) found that technological progress such as improved irrigation systems, use of greenhouses for growing crops, and improvement in seed production could counterbalance any increase in crop water demand caused by the increase in ET_o in China. However, in the Tibetan Plateau region and northeast China, the increased ET_o overwhelmed the beneficial effect of technological progress, causing negative effects on crop productivity (Lobell et al. 2011; Wang et al. 2017). Therefore, a drying condition and increasing ET_o trend will likely require new management strategy for sustaining water resources in the QRB.

CONCLUSIONS

Identifying the individual climatic control on ET_o helps to understand the processes of global climatic change impacts on local water resources and also simplify modeling efforts to predict actual ET. This long-term study (1961–2012) shows that ET_o over QRB under a humid climate has changed over the past 52 years: decreasing during 1961–1987 and then increasing during 1988–2012. Prior to 1987, decreased WS, R_s, VPD, and increased RH were responsible for the negative trends of ET_o. The positive trends of ET_o during 1988–2012 were mainly caused by effects of decreased RH and increased VPD. The decreased AH and increased air temperature also contributed to the increased ET_o to a lesser degree.

In general, our findings indicated that the climate in QRB has become drier during 1988–2012. Our study has important implications for watershed management in these paddy field-dominated humid regions, where actual water loss is mainly controlled by atmospheric demand (i.e., energy-limited hydrological systems). The increasing ET_o indicates an increase in irrigation water demand by the paddy rice, a main crop in southern China. This increased water use has the potential to cause water shortage problems especially during drought events that are not uncommon in the study basin. For the humid regions elsewhere, similar studies should be carried out to assess the impacts of climate change on ET_o variation.

Future water management must consider the recent shifts of climatic control on the hydrological cycles in southern China. Because atmospheric demand (VPD) is a major control on potential water loss over the humid wet region, predicting hydrological change under a changing climate must consider both air humidity and air temperature. Climate predictions from General Circulation Models must be assessed for their accuracy to simulate VPD in addition to air temperature and precipitation. In addition, reference ET algorithms that are often embedded in watershed hydrological models (such as PRMS, HBV, DTVGM, HIMS SWAT, and TOPKAPI) (Zhao et al. 2013) must include VPD as a major climatic input variable to fully account for atmospheric water demand and actual ET.

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